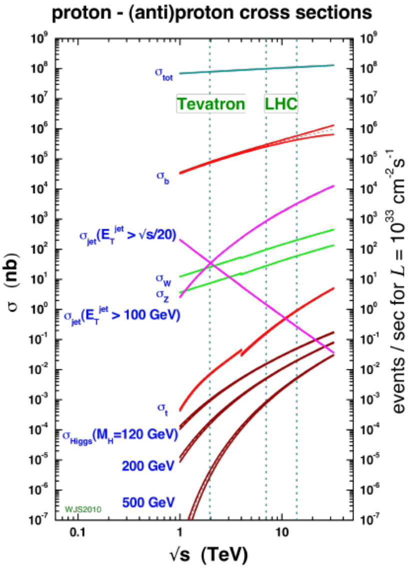
Lecture 23: Hadron Collider Physics (II)

Nov 15, 2015

Include slides on Top taken from
Gianluca Petrillo's talk at Moriond 2013

Reminder: Cross Sections at Hadron Colliders

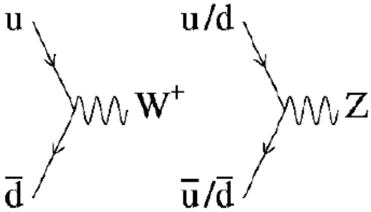


- Rates determined by
  - Hard Scattering Cross Section
  - Parton luminosity
- QCD processes dominate
  - EW rates lower by α/α_S
- Main background for W and Z production: QCD jets
- Almost impossible to see single $W \to q\bar{q}'$ or $Z \to q\bar{q}$ above jet background
  - UA2 managed to do this with special trigger and very large background
  - But almost all studies of W and Z in hadron colliders in leptonic decay modes

$$W^\pm \to \begin{array}{c} \ell^-\nu_\ell \\ \ell^+\bar{\nu}_\ell \end{array}$$

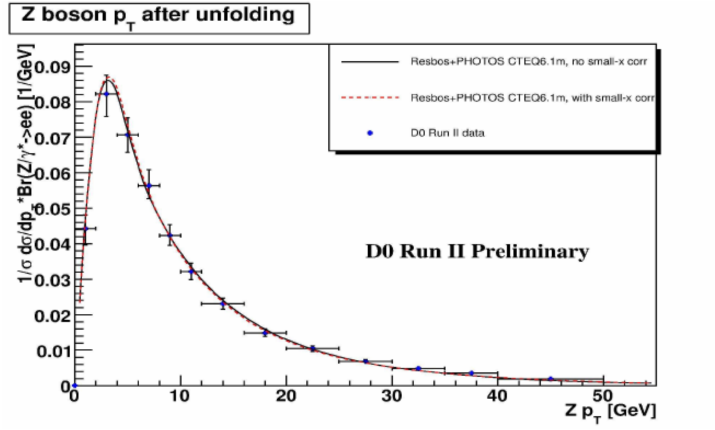
$$Z \to \ell^+\ell^-$$

Production of W and Z Bosons



- Lowest order diagram: quark annihilation
- At lowest order, W and Z are produced with no p_T

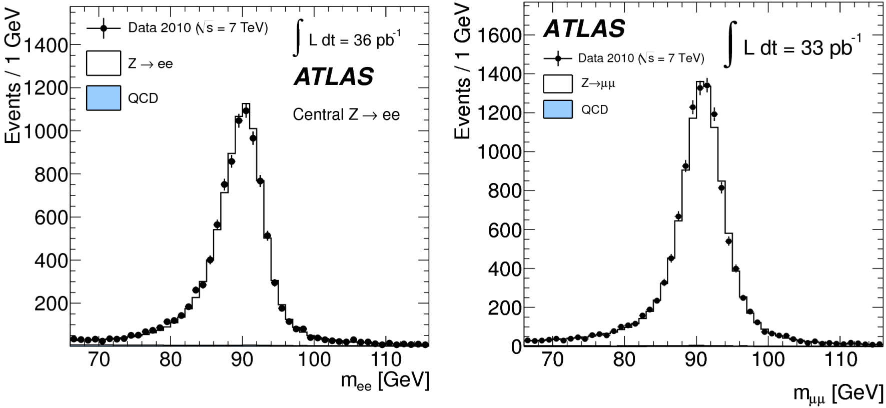
Full QCD Calculation: Boson p_T Remains Small



Distribution dominated by multiple soft gluon emission

Reconstruction of Z Bosons

- In general, limited to leptonic modes
  - Large QCD jet background swamps signal in jet channel
  - In principle, can find regions of phase space where hadronic mode can be reconstructed, but in very specialized analyses with other objects
  - Two high p_T leptons, nearly back-to-back
  - Reconstruction straightforward, background small



Reconstruction of W Bosons

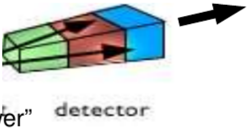
- Again, restricted to lepton channels
- But here, one of the nearly back-to-back leptons is a neutrino

  How do we "detect" a particle that doesn't interact in our detetor?
- Look for momentum imbalance and assign the missing momentum to the ν

  But in hadron colliders, limited to using only the 2 transverse components of the momentum

Neutrino Reconstruction

- Must add the momentum of all objects in the event
- The traditional way: calorimeter only



Calorimeter "Tower"

Define $\not{E}_T$ (2 vector)

$$\begin{aligned}\not{E}_T &= -\sum_{\text{Towers}} E_{iT}\hat{n} \\ &= -\sum E_i \sin\theta_i \hat{n}\end{aligned}$$

Similarly total E_t

$$\begin{aligned}E_t &= \sum_{\text{Towers}} |E_{iT}| \\ &= \sum |E_i| \sin\theta_i\end{aligned}$$

  - Create a grid of calorimeter towers
  - Treat each tower as a massless particle with momentum direction normal to the tower

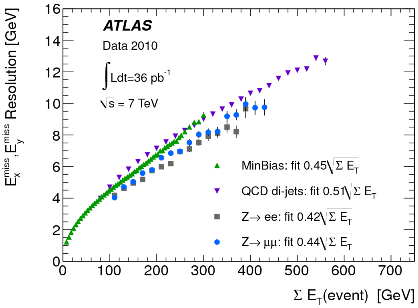
- For better resolution: Use reconstructed objects
  - Combine the momentum of all the jets and electrons, muons
  - Then add the remaining unused energy using towers as above
  - When combining, can have different calibrations to each object

A Comment on Resolution

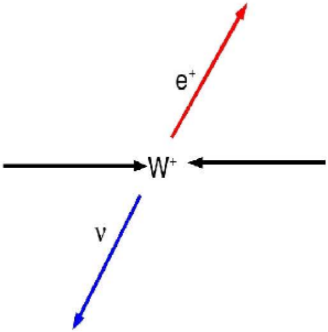
- Calorimeter resolution depends on energy deposited

$$\sigma_{/E_T} \propto \sqrt{\sum E_T}$$

- Measurement is also sensitive to detector cracks and noise
- Degrades with pileup



W Decay: Lepton p_T Distribution



- In CM frame, e and ν are back-to-back and balance p_T:

$$ {p_T}^2 = \frac{1}{4}\hat{s}\sin^2\theta $$

- Changing variables from $\cos\theta$ to p_T introduces a Jacobean:

$$ \frac{d\cos\theta}{dp_T^2} = -\frac{2}{\hat{s}\cos\theta} $$

- But we know

$$ \frac{d\sigma}{d\cos\theta} \propto \left(1+\cos^2\theta\right) $$

so

$$ \frac{d\sigma}{dp_T^2} \propto \frac{\left(1+\cos^2\theta\right)}{\hat{s}\cos\theta} \propto \frac{2\left(1-2p_T^2/\hat{s}\right)}{\hat{s}\left(1-4p_T^2/\hat{s}\right)^{\frac{1}{2}}} $$

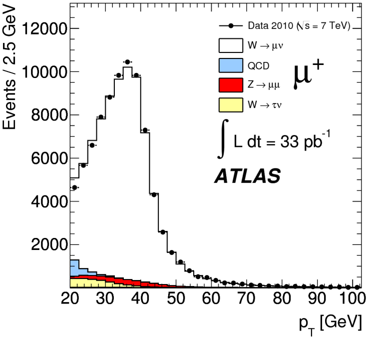
The Jacobean Peak

- Notice

$$\frac{d\sigma}{dp_T} \propto \frac{1+\cos^2\theta}{\cos\theta}$$

Diverges for $\theta = \pi/2$ (which is $p_T = \sqrt{\hat{s}}/2$)

- Diverence results from the Jacobean factor in tranformation to p_T
- Integration over Breit-Wigner removes singularity but leaves the peak
- HO corrections give W transverse momentum and further smear the peak



Transverse Mass

- W p_T gives ℓ and ν by same boost
- Define ℓ-ν transverse mass:

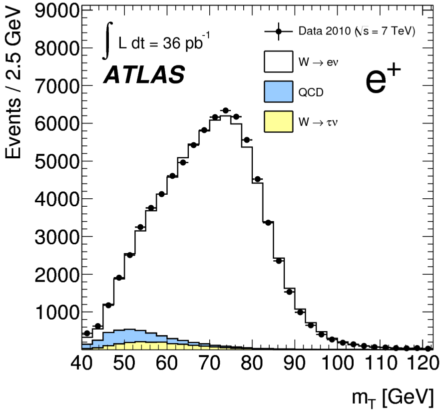
$$m_T^2 = (E_T^\ell + E_T^\nu)^2 - (\vec{p}_T^{\,\ell} + \vec{p}_T^{\,\nu})^2$$

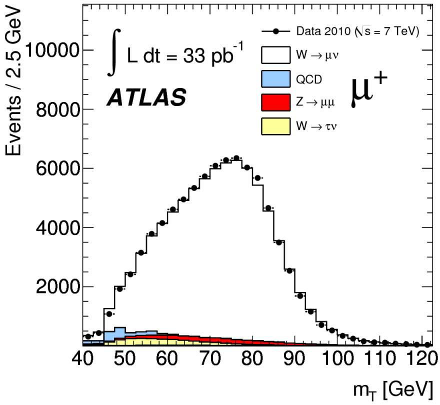
- Note that for $p_T^W = 0$, $m_T = 2|p_T^\ell| = 2|p_T^\nu|$
- Thus

$$\frac{d\sigma}{dm_T^2} = 4\frac{d\sigma}{dp_T^2}$$

- m_T sensitive to transverse boosts only at second order
  - Predicted m_T distributuion not very sensitive to modeling of boson p_T
- But m_T more sensitive to detector resolution since depends on measurement of the ν

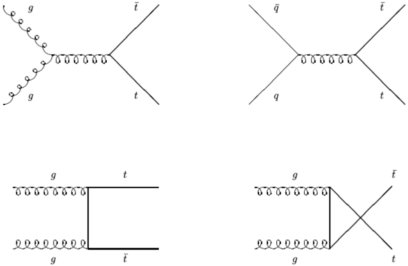
Transverse Mass for W Bosons





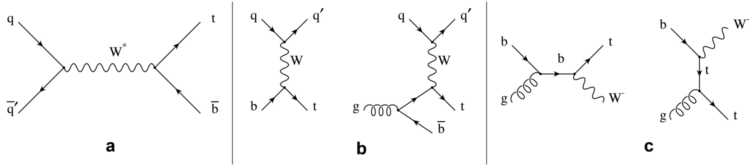
- Background small in both e and μ channels
- Small theoretical uncertainties: a better choice of variable than lepton p_T in most cases

Top-Pair Production



- Strong production: $t\bar{t}$ pairs
- Tevatron: ($p\bar{p}$ collder)
  - Production rate suppressed: $2m_{top} \sim 0.2\sqrt{s}$
  - 15% gg, 85% $q\overline{1}$
- LHC: (pp collider)
  - Production rate larger $2m_{top} \sim 0.05\sqrt{s}$
  - 90% gg, 10% $q\bar{q}$

Single Top Production Through EW Processes

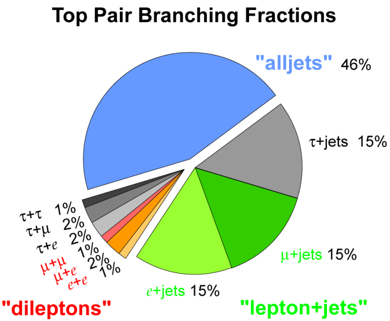


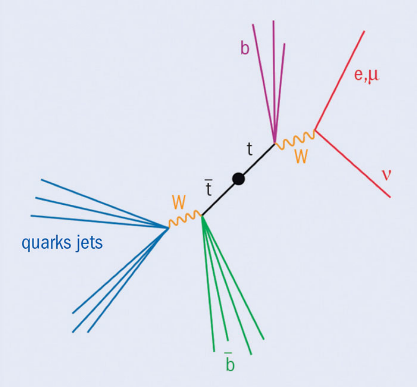
- Characterize as "s-channel", "t-channel","$W+t$"
- t-channel is the largest contribution, s-channel the smallest
- More difficult to isolate than the strong pair production
- Will concentrate on $t\bar{t}$ production for most of today, but will return to this process towards the end of the lecture

Top Decay Signatures ($t\bar{t}$ Production)

- $t \to Wb$ BR$\sim 100\%$ in SM (V_{tb})
- Top lifetime $\sim 5 \times 10^{-25}$ sec

  Decays before hadronization
- Top Pair production gives:





Top Reconstruction: The Basics

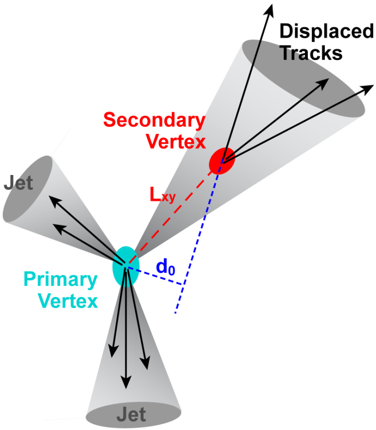
- Top pairs yield 6 high p_T objects
- Separate search strategies for dilepton, single lepton and all hadronic channels
  - Dilepton clean, but 2ν's so full mass reconstruction not possible
  - Single lepton: Good S:B. The golden channel
  - All-hadronic: Must separate from very large QCD multijet background: possible with b-tagging, but difficult to get a pure signal

Top Analysis Strategy

- Goal: Maximumize top signal while reducing QCD background
- Top decay products central and at high p_T
  - Typical Tevatron cuts: $p_T > 15$ GeV
  - Typical LHC cuts: $p_T > 25$ GeV
- Di- and single lepton channels have missing E_T
  - Define $H_T = \sum_i E_T$ where sum is over reconstructed objects
- Two b-jets in final state: identification of b's greatly reduced background rate

Jets Produced from b-quarks

- Characteristics of B decays':
  - B lifetime long
  - Semileptonic BR 10% per species
- Two methods of b-tagging
  - Displaced vertex tag
  - "Soft" leptons inside jets
- Today, multivariant techniques combine all information into a single metric

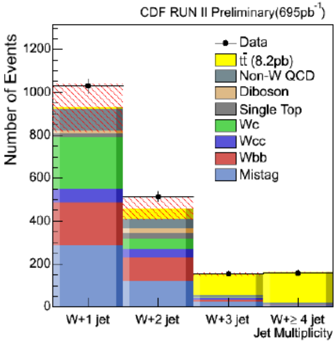


Reconstructing Top in Single Lepton Channel

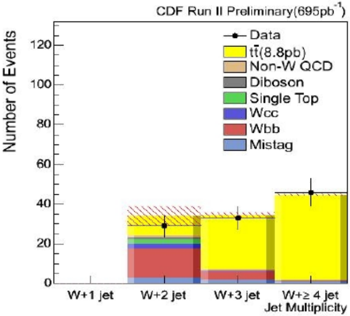
- Sample contains lepton, missing energy and ≥ 4 jets

  (additional jets from initial or final state radiation)
  - 2 jets reconstruct to W mass
  - $\ell + \nu$ reconstruct to W mass
    (must use transverse mass since p_z^ν not measured)
  - 2 jets are b-jets
  - Each $W + b$ reconstructs to a top
- Many possible combinations of objects possible
  - Can apply constraints to pick the best combinatorial choice
  - Or can use all choices, weighting with probability
- Signal can be observed without b-tagging if high H_T cut applied
- But b-tagging reduces combinatorial background

With b-tagging, Top dominated sample was selected at the Tevatron

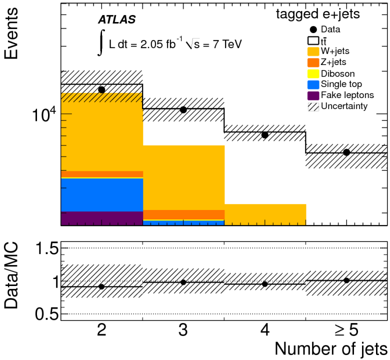


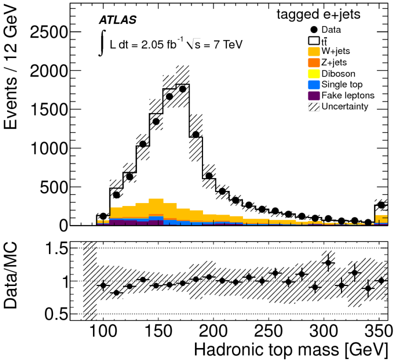
Single b-tag and HT>200 GeV



Double Tag

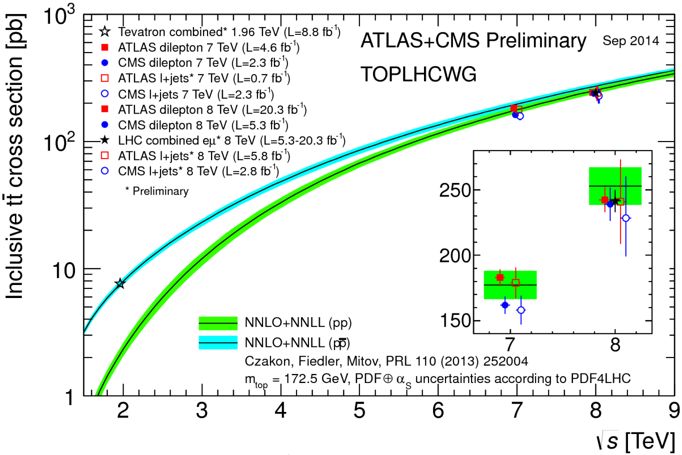
At LHC, large, clean samples available





- Above require single b-tagged jet
- Right hand plot after kinematic likelihood fit and requirement of at least 4 jets

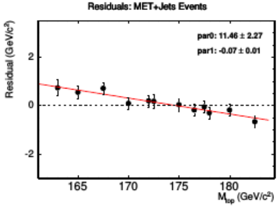
Top Pair Cross Section



- Good agreement with pQCD predictions
- Important since top a major background to BSM searches

The measurements of top mass goes through some common steps:

1. assign a likelihood for each event, function of the top mass: $L_i\,(m_t;\,\ldots)$
2. maximize a global likelihood $L\,(m_t;\,\ldots) = \prod_{i\in\text{events}} L_i\,(m_t;\,\ldots)$, including all the events, to extract the m_t estimator
3. calibrate to remove any bias of the method



Calibration curve of m_t from CDF measurement from 8.7 fb^{-1} *in* $\not{E}_T$ +jets

- our analyses are calibrated on Monte Carlo simulation

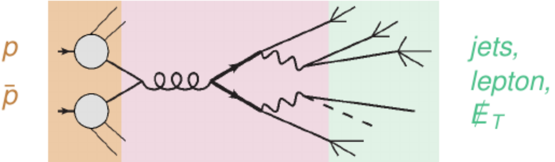
$\Rightarrow$ we measure m_t with the definition implemented in MC!

- the precision of the experimental measurements helps the *interpretation* of this parameter *(cfr. PRD **80**, 071102 (2009))*

Matrix Element method exploits the full topology of the event:

$$P(x, m_t) = \frac{1}{\sigma(m_t)} \int \sum_{\text{flavours}} f(q_1)\, f(q_2)\, \sigma(y, m_t)\, \mathcal{W}(x, y)\ dq_1\, dq_2\ dy$$

scattering matrix element (in σ) for a final-state parton configuration "y" (including 4-momenta of all the 6 final state particles)

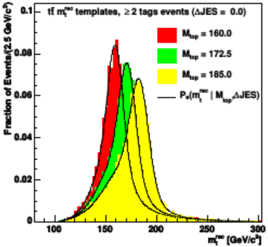


probability $f(q_{1/2})$ of having a specific initial state (*Parton Distribution Functions*)

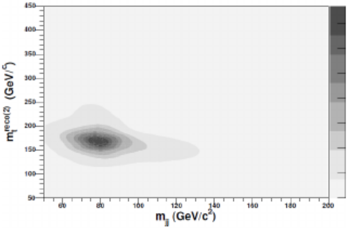
probability $\mathcal{W}$ of reconstructing the scattering final state "y" as our measured jets/lepton objects "x" (*Transfer Functions*)

Templates method interprets the distribution of one or more observables sensitive to m_t as probability densities:

- distributions are extracted from full detector simulation
- correlations between observables *can* be included
- up to three observables used



m_t template (CDF measurement from 5.8 fb^{-1} *in all-hadronic final state)*

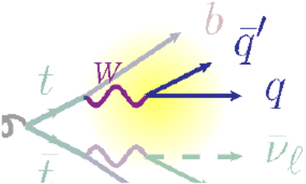


*m_t vs. m_{jj} template (m_t=*171.5 GeV/c^2*) from CDF measurement from* 8.7 fb^{-1} *in ℓ+jets*

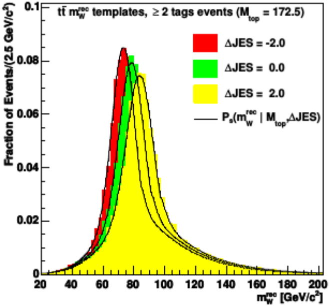
- in some final states, W boson can be *fully reconstructed*

⇒ constrain a m_W estimator with the known W mass

- "nuisance parameter" Δ_{JES} is measured, describing an additional global scale of jet energy

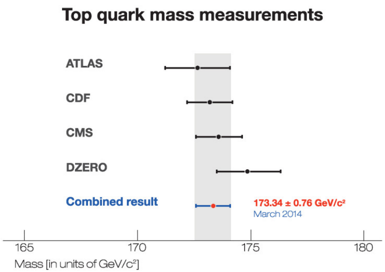


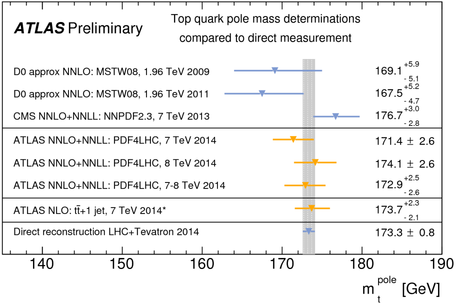
$t\bar{t}$ diagram with $W \to q\bar{q}$



m_{jj} template (CDF measurement from 5.8 fb^{-1} in all-hadronic final state, m_t=172.5 GeV/c^2)

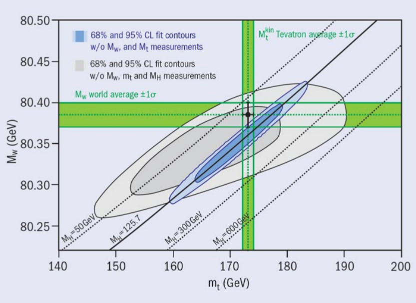
Top Mass Measurement Summary

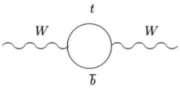


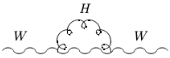


- Good agreement between experiments for direct measurement of m_{top}
- m_{top} derived from cross section consistent with direct measurements

Why does m_{top} matter?

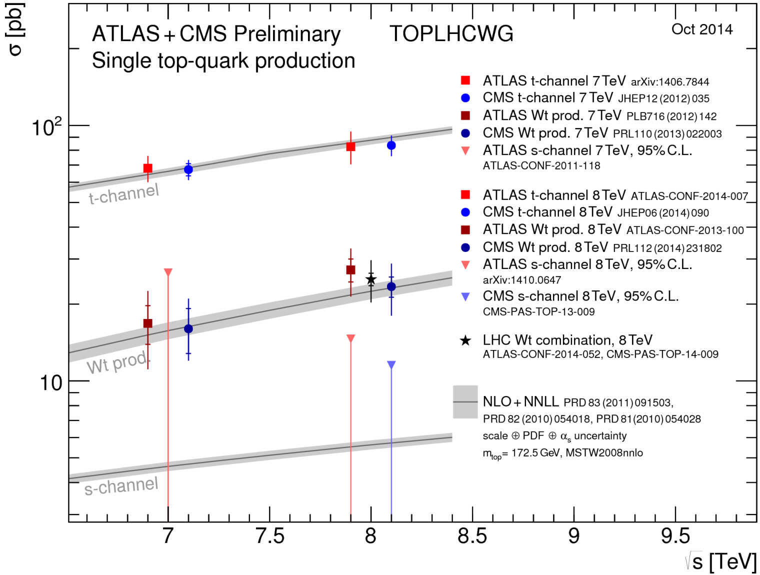






- m_W depends quadratically on m_{top} and logrithmically on m_{Higgs}
- Would also be sensitive to other BSM particles with moderate mass
- Before Higgs discovered, gave prediction for its mass
- Now, can constrain possible BSM physics

Single Top Production



Using Top to Search for New Physics